AGN relics in the radio sky

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Chapter 8

Summary and future prospects

The Great Way is gateless,
approached in a thousand ways.
Once past this checkpoint, you
stride through the universe.

– Wu-wen kuan

In this work we have shown the variety of relic structures formed as a consequence of AGN activity. We have demonstrated the use of multi-wavelength data to put constraints on aging models and derive radiative ages of relics. Also, we have shown that new facilities like the LOw Frequency ARray (LOFAR; van Haarlem et al. 2013) which operate at the lowest frequency end of the radio spectrum can be very useful in both discovering new relics and tracing out the oldest particle populations in known relics and helping to constrain our modeling.

Below we give a systematic overview of AGN properties and their relation to AGN radio relics. We conclude with our findings and outline a path for future studies, having in mind the availability of novel facilities such as LOFAR.

8.1 The AGN - relic connection

AGN radio relic properties obviously depend on the specifics of the past active phase of the radio source. The most obvious morphological division of radio sources is the Fanaroff & Riley (1974) classification scheme, dividing radio sources into two categories: FRI and FRII. FRI sources are characterized by a bright radio core, flaring jets, no hotspots, they tend to be brighter toward the location of the AGN and have spectral indices which are steeper going outward from the host galaxy. The FRII sources have sometimes a noticeable radio core, tightly collimated relativistic jets, clearly delineated hotspots where the jets end and plasma lobes surrounding the jets/hotspots. Typically, the surface brightness of these sources peaks at the hotspots located symmetrically w.r.t the host galaxy. The specific radio luminosity which divides these two classes is $L_{1400MHz} \sim 10^{24} - 10^{25}\mathrm{WHz}^{-1}$, although this division is not sharp. Best (2009) has shown that more massive galaxies are more likely to host a radio source, but that the luminosity of a radio source is largely unrelated to the mass of the host galaxy.

The spectral properties of optical AGN and their relation to the radio phenomenology is also ambiguous. The fraction of galaxies hosting an AGN as identified from their optical spectra (emission line AGN) shows no dependence on the mass of the host galaxy (Kauffmann et al. 2003). Best et al. (2005) show that the probability of an AGN being radio loud is independent on whether it is classified as an emission line AGN or not.

With respect to radio power, low luminosity radio sources are predominantly powered by radiatively inefficient (low excitation, advection dominated accretion, jet mode accretion) AGN. Conversely, high luminosity radio sources are predominantly powered by radiatively efficient (emission line, high excitation, radiative mode accretion) AGN. The radiatively inefficient accretion probably arises by (relatively small amounts of) hot gas acreting onto a Super Massive Black Hole (SMBH), while the radiatively efficient accretion is though to arise from higher accretion rates of (cold) gas onto a SMBH.

Relative to the radio morphology, most of the FRII radio galaxies are powered by radiatively efficient (emission line, high excitation, radiative mode accretion) AGN, while most of the FRI radio galaxies are powered by radiatively inefficient (low excitation, advection dominated accretion, jet mode accretion) AGN. The radiatively inefficient AGN show no sign of a quasar (visible or hidden) at optical, infrared or X-ray wavelengths (Hardcastle et al. 2007), but some FRIs have quasar nuclei. Best & Heckman (2012) show that FRIIs occur in somewhat less massive and somewhat bluer host galaxies than FRIs.

Hence, the initial accretion (and AGN triggering) mechanism is probably unrelated to the large scale radio morphology. Best (2009) finds that, in his sample, FRII sources are in general smaller than FRIs. He suggests that all radio sources start their life as young (CSS, GPS) FRIIs. In some cases, their relativistic radio jets are later disrupted (decollimated) by the host galaxy ISM and they become FRIs with lower radio luminosity. The fact that CSS source morphologies do show symmetric structure reminiscent of FRIIs seems to support this suggestion.

The nature of the AGN accretion and triggering mechanisms is related to the expected morphology of relic structures, whether the radio source (and relic) morphological type changes between activity episodes and to the specifics of the AGN duty cycle. In relation to what was discussed above, based on the radio source morphology, we can summarize the relic-related radio source properties as follows:

- FRI radio sources have lower radio luminosities and their AGN are predominantly hosted by massive elliptical galaxies which are members of galaxy clusters. There are no known instances of FRI radio relic faders. Several instances of restarted FRIs are known, one of which is 4C 35.06, studied in Chapter 3 of this thesis.

- FRII radio sources have higher radio luminosities and their AGN are generally hosted by less massive field galaxies. So far, we know of just one well studied case of an FRII relic fader in the field (B2 0924+30, studied in Chapter 5 of this thesis). In some cases (steeper spectral index of the outer pair of radio lobes w.r.t the inner ones) the double-double radio galaxies (DDRGs) could be thought of as restarted FRIIs.

Statistical studies of the luminosity of radio sources (Best et al. 2005; Shabala et al. 2008) demonstrate that FRII radio galaxies are switched off for one to few Gyr, while FRIs seem to have a duty cycle of $t_{off} < 3t_{on}$. These observations might provide a clue for the scarcity of (FRII) radio relics in the field. We would only be able to detect them in the short time before they fade from view.

Studies by Dwarakanath & Kale (2009) and Best et al. (2005) show that we should be able to observe many more AGN radio relics than we do now. However, AGN radio relics are scarce, and the reasons behind this are still a mystery. If adiabatic energy losses are responsible for the very fast fading of relics, it may explain their scarcity, but there is no clear evidence that the a substantially larger number of relics is observed in cluster environments vs. the field, even though there are hints in surveys pointing in this direction. A possibility exists that our current radio surveys (even the low frequency ones) are not sensitive enough.

Radiative aging studies performed on radio relic faders were carried out by Parma et al. (2007) on six faders and three restarted relics. The duration of the active phase was estimated to be in the range of 10^7 - 10^8yrs. with the duration of the inactive period an order of magnitude shorter. No clear dependence was observed w.r.t environment (cluster vs. field).

Murgia et al. (2011) find that in their sample of five radio relics hosted by galaxies belonging to clusters, three have a duration of their inactive periods which is longer than the active radio phase, and for the rest the inactive period lasted a third of the active period. Compared to the field sources studied by Parma et al. (2007) it seems that radio relics in clusters tend to have longer lifetimes, maybe because of radio plasma confinement mitigating the energy losses. Morphologically, the sources WNB 1734+6407 and B2 1610+29 in the sample of Murgia et al. (2011) resemble FRII relics; B2 1610+29 has also a spectral index profile consistent with it being a FRII relic. The other sources show morphological and spectral characteristics of FRI relics (possibly with restarted cores). Murgia et al. (2011) have also merged the statistics of their sample and the Colla et al. (1972) complete B2 bright sample and have found that the probability of a radio relic fader being located in a cluster is around 80%. This might indicate that the hot cluster gas is confining the plasma and decreasing or stopping its expansion, thus extending the radiative lifetime. Another possibility is that radio sources hosted by cluster galaxies have shorter duty cycles, so at any given time they will present an observable AGN radio relic emission.

Giacintucci et al. (2007) have studied seven radio relics (faders and restarted) hosted by cD galaxies in clusters. Their results in general agree with those of Murgia et al. (2011) in that the derived relic ages are larger than those observed in field galaxies. Most of the fader sources in the sample show characteristic spectral index profiles suggesting that these relics can be thought of as being remnants of FRI radio galaxies.

How do all these pieces of radio morphology, size, triggering mechanisms, environment and distance fit in the AGN radio relic puzzle? Notwithstanding the inter-dependencies between these factors, one possible overview would be the following.

- **Morphology.** Assuming that all radio sources start as FRIIs, a fraction of them whose jets are de-collimated will grow to be FRIs, with the rest having a large scale FRII morphology. It may be that jet de-collimation is more likely in massive cluster galaxies, which would explain the association of FRI radio galaxies (and their relics) with massive cluster galaxies.

Studies of Murgia et al. (2011) and Giacintucci et al. (2007), the radio morphology of the 4C 35.06 source (Chapter 3) as well as that of 3C 388 are relevant cases in this point, showing aged radio sources in clusters, sometimes restarted, which tend to be older than sources in the field. The notion that FRI radio galaxies have duty cycles characterized by short inactive epochs and activate more frequently may explain why there is a tendency to find relics of radio loud galaxies (possibly of FRI type) on average slightly more often in clusters than in the field.

As we have noted before, FRII radio relics are sparse. This may be because FRII radio galaxies tend to be found more in the field (as mentioned previously) where any radio relics quickly fade away. Based on the recent work of Eilek (2014), the maximum electron radiative lifetime assuming a reasonable value of the magnetic field would be between 150 and 200 Myr. After that, the relics would fade away and be undetectable. In our study of the AGN radio relic B2 0924+30 we have shown that the outer lobes are as young as 20 Myr. Even though in this case it seems that radiative and Inverse Compton (IC) energy losses are dominant, it may be that in the future expansion losses will take on the dominant role and this relic will disappear fast (as may already have been the case with others similar relics). A duty cycle characterized with longer inactive periods will contribute to these sources being more difficult to observe at any given epoch; they will only be visible for a short time after the end of the active phase. If the (cold gas) fueling of FRIIs is connected to galaxy mergers, the period between two consecutive activity epochs would be on the order of a Gyr (as mentioned previously).

As a side note, the large scale, low surface brightness relic discovery which we have discussed in Chapter 2 of this work is associated with a CSS source, B2 0258+35, which has an FRI morphology. If the proposition of Best (2009) holds, it follows that its jet de-colimation has happened very close to the AGN.

- **Size.** A fraction of the AGN would shut down after a short period of activity due to lack of fuel, and possibly restart again. We would expect to see the radio relics from this brief active phase as relics around young, CSS or GPS sources. Previous studies have shown that small-scale relics around compact sources are scarce; this may be due to the fact that in majority of cases the AGN active timescale is not so short, or it may be a selection effect - looking for small-scale AGN radio relics around currently active compact sources (and being able to see them) would require that the AGNs stop their previous active phase in a relatively short time and restart again before the relic fades away. This would naturally limit the number of relics observed. Our low frequency search for large radio relics around young compact sources (elaborated in Chapter 6) has not uncovered new relics, although this result is probably biased by our sample selection and the limited sensitivity and spatial resolution of the MSSS survey we have used.

- **Triggering.** It is not very clear what is the relation of cold gas and in particular H I to the AGN duty cycle. We have discussed the large reservoir of cold gas found around the host galaxy and in the vicinity of the CSS source B2 0258+35 in Chapter 2. Also, the H I absorption profile found in the host galaxy of 4C 35.06 was discussed in Chapter 3. The kinematics of the gas in these cases suggests no connection with previous AGN activity or AGN re-start. The presence of cold gas hints at a supply which may fuel the AGN activity, even though the gas transport mechanisms to the AGN are less clear and remain an open issue at the moment. However, several studies suggest that the occurrence of H I in the central regions of restarted radio sources is higher than in other radio sources (Saikia & Jamrozy 2009; Chandola et al. 2010; Geréb et al. 2013).

Konar et al. (2013) have found that the inactive phase of two DDRGs they have studied (hosted by field galaxies) lasted only a few percent of the active phase, which is in stark contrast to the duty cycles discussed above. The reasons why these field radio galaxies are so different in this respect, and whether they are just outliers will need more study to be ascertained with any certainty. It is certainly possible that within broad subgroups or relic/re-started radio sources finer variations exist which blur the clear demarcation lines that we are discussing.

- **Environment.** Independent of other variables, denser cluster environments may prolong the fading timescale. This may be a contributing factor why we are seeing more large scale relics in cluster environments and why field galaxy hosted relics are scarce. However, much more studies are needed (and especially large relic samples) before we can claim any conclusive results.

- **Distance.** Tasse et al. (2008) have shown that lower luminosity, FRI radio galaxies are connected to galaxy overdensities at $z = 0.5$, consistent with what we observe locally. However, the recent work of Hatch et al. (2014) and Wylezalek et al. (2013) notes radio galaxies consistent with observed $L_{500MHz} = 10^{27.5} - 10^{29}\mathrm{WHz}^{-1}$ specific luminosities associated with galaxy clusters at $1.3 < z < 3.2$. These luminosities correspond to FRII radio galaxy luminosities. This result suggests (barring any selection effects) that at higher redshifts in cluster environments FRII radio galaxies are (at least) equally abundant as FRIs, indicating evolution with redshift of the radio galaxy population in cluster environments. The implications of this result on AGN radio relics would be that FRII relics dominate high redshift clusters of galaxies, as opposed to FRI type relics locally.

8.2 Results and future work

We have given an overview of and summarized the most important AGN properties as they relate to AGN radio relics, and have gone over the interdependencies of various astrophysical properties which influence the AGN duty cycle and relic properties. In this thesis, we have studied various types of AGN radio relics to constrain their properties and quantify the AGN duty cycle and any environmental influence on the relic properties.

- In **Chapter 2** we have investigated a very low surface brightness relic discovered around the young Compact Steep Spectrum (CSS) source B2 0258+35. It is a very interesting relic, since it is relatively large for relics typically reported around CSS sources. It also shows a distinct lobed appearance, suggestive that it may still be connected to the central source and re-fueled at a very low level of activity. Under the assumption that it is a rising relic bubble, we have been able to derive its dynamical age and estimate the accretion rate of the CSS source, both estimates agreeing with literature values.

Assessment of the radiative ages should follow using follow-up observations, preferably at low frequencies. The relic structure has been detected at 150 MHz using LOFAR (Marisa Brienza, private communication). More relics may be discovered around compact sources, this may be just an example of why we have not been able to detect them so far, they may be too faint at high frequencies and present observational difficulties since they are located in the vicinity of a bright source.

- **Chapter 3** discusses a serendipitous discovery of extended steep spectrum emission connected to the radio galaxy 4C 35.06. The observations were performed in the LOFAR LBA band around 60 MHz as part of the commissioning activities and have actually been centered on the target discussed in Chapter 2. This demonstrates the added value of the large LOFAR field of view; we present an analysis of the radio source properties in this field in Appendix A.

  We were able do determine that the source has an unusual helical morphology and that it is a restarted FRI source. We have shown that its outer regions have extremely curved spectra and were able to quantify the contribution of various source regions to the integrated source spectrum. Such insight can prove useful when searching for relics or restarted radio sources; the integrated spectrum properties (steepness as it relates to curvature) can be a useful tool in such a search. Benchmarking these tools on resolved sources which we can study in detail is a necessary step which we have performed in our study.

- **Chapter 4** showcases a targeted study of an AGN relic (J1431.8+1331) located in a cluster of galaxies. We have extended previous studies of this intriguing object to the lowest frequencies to date (around 150 MHz, using the LOFAR HBA band) and have derived low frequency spectral index, spectral curvature and spectral aging maps. We have showed that radiative aging is the dominant energy loss mechanism, possibly a sign that the hot gas in the cluster is constraining the radio plasma expansion. Our results are in line with fading timescales derived for cluster relics. For this particular source, we have been able to show that two distinct source regions have different radio emission origin: AGN relic and a shock wave compressed plasma bubble, underlining the value of spatially resolved low frequency observations.

- **Chapter 5** studies a very rare AGN relic type, B2 0924+30, which shows an aged FRII morphology. It is the only known relic of this type. Our spatially resolved LOFAR HBA data were again instrumental to demonstrate its FRII origin and to constrain the time of cessation of AGN activity to around 150 Myr ago. We have been able to derive the highest resolution spectral index and age maps at low frequencies. Interestingly, we have shown that for this field relic the dominant energy loss mechanisms are still radiative losses.

- **Chapter 6** outlines our use of the preliminary LOFAR Multi-frequency Snapshot Sky Survey (MSSS) maps to search for AGN radio relics around young (CSS and GPS) radio sources. We have been able to detect several known giant radio galaxies, but due to the limited sensitivity and resolution we have not discovered any new relics near compact sources. Even so, we have placed constraints in that a moderate surface brightness relic population does not seem to exist around the neraest compact sources, which supports the results of Chapter 2.

- In **Chapter 7** we have performed the first of its kind low frequency (150 MHz, LOFAR) high resolution study of two giant radio galaxies, 3C 236 and NGC 6251. We have studied the spectral index and discovered a counterjet connecting the core region of NGC 6251 to its south-eastern lobe as well as mapping extended emission on the outskirts of its lobes. We have also mapped the curved spectrum of the region close to the core in the north-western lobe of 3C 236, and have confirmed that the inner lobe region has injection index spectral indices ($\alpha \propto -0.6$) at low frequencies.

These results demonstrate the usefulness of LOFAR as a relic survey instrument thanks to its unprecedented sensitivity at low frequencies, as well as the high imaging resolution. Our discoveries showcase its abilities. We have discovered unknown steep spectrum sources in almost every LOFAR pointing, maybe a hint of an unknown low surface brightness relic population.

In the future we would like to address the still unanswered questions pertaining to the AGN radio relics and also contribute towards gaining more insight into their properties. In summary:

- What are the ON and OFF timescales for the AGN activity (the AGN duty cycle)?
- Does the duty cycle depend on the AGN environment (AGNs in clusters vs. AGNs in the field)?
- For resolved sources, what is the age of the radio plasma across the source?
- How do the properties of the integrated radio spectrum change over the lifetime of the AGN, and can these properties be used as a diagnostic tool to infer the ages of source components for unresolved / high redshift radio sources?

Such questions require much larger AGN radio relic sample sizes to be answered conclusively. Due to the nature of the non-thermal emission, the AGN radio relics are more likely to be found at lower frequencies. As we have demonstrated, the LOFAR telescope is providing science-worthy data and should provide the sample sizes we need, as a precursor for the SKA which will really open up the skies for these studies.

The MSSS survey (Heald et al. 2014, submitted) has proven that LOFAR is ready for such surveys. However, we may need better sensitivity to really uncover the relic population. This means that the LOFAR tier 1 and 2 surveys should begin the proper characterization of the AGN radio relic population. A hint of this is already apparent; our dedicated high sensitivity LOFAR observations have already uncovered several new relic candidates. We will also need multi-frequency follow-up of any relic discoveries if we wish to model the radiative aging process or disentangle between the predictions of different models.

In general, there is a trend for the re-starting of AGN to happen more often for AGN hosted by galaxies in clusters. This may be even more so for AGN hosted by multi-core cD galaxies in clusters. A systematic LOFAR observation of all of these objects should allow us to check this hypothesis and lead to better understanding of AGN activity triggering/feedback in these systems.

Following up on our studies of relics around compact sources is essential to put constraints on the duty cycle of these sources, and to explain the relative relic scarcity around